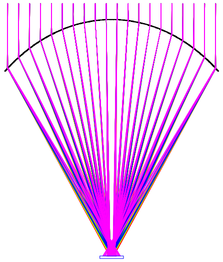
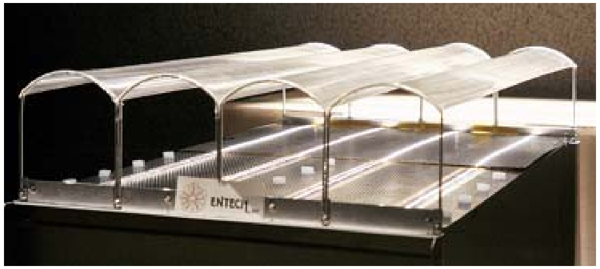




Acknowledgment: This Work Builds on Several Previous NASA Programs

1,000 W/kg Concentrator Study and Roadmap for SSP

Selected for Funding Under the NASA-NSF-EPRI Joint Investigation of Enabling Technologies for SSP (JIETSSP) Program Announcement NSF-02-098

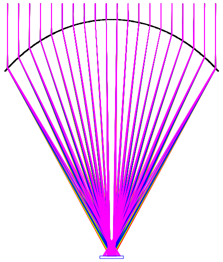
Presented at the Space Solar Power Concept & Technology Maturation (SCTM) Program Technical Interchange Meeting (TIM)

Ohio Aerospace Institute
September 10-12, 2002

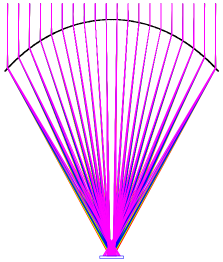
M.J. O'Neill
ENTECH, Inc.
1077 Chisolm Trail
Keller, TX 76248 USA
Tel: 817-379-0100 Fax: 817-379-0300
E-Mail: mjoneill@entechsolar.com
Web Site: www.entechsolar.com

U.S. Patents 4,069,812, 4,711,972, 6,031,179, and 6,075,200.

ENTECH, INC.



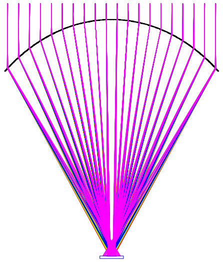
Program Team and Plan



Study Team

- **Industry**
  - **ENTECH: Prime Contractor and Study Team Leader**
- **NASA**
  - **NASA Glenn: Study Support and Educational Outreach Coordination**
- **Educational Outreach Partner**
  - **Assumption School – Cleveland, Ohio**

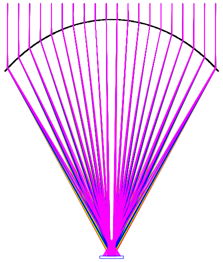
ENTECH, INC.



Program Objectives

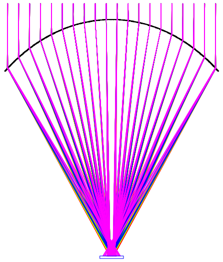
- **To generate candidate designs of advanced photovoltaic concentrators which are capable of meeting the performance requirements for SSP, including the specific power target of 1,000 W/kg.**
- **To perform optical, thermal, and mass analyses of the candidate designs to identify the necessary thicknesses for the optics, radiators, and cell assemblies, to verify adequate performance of these items, and to estimate the areal mass densities (kg/sq.m.) for the candidate designs.**
- **To generate a roadmap of the necessary concentrator development program to move from the conceptual designs of this program to prototype components to functional ground-test panels to flight-qualified arrays.**

ENTECH, INC.



Technical Approach

- For optical studies, use ray trace programs, which include the effects of solar disk size, spectral content of the solar irradiance, optical properties of the concentrator material, and quantum efficiency curves of the multi-junction solar cells. These programs have been used successfully to analyze and design many previous concentrator systems, including the mini-dome lens array on PASP+ and the SCARLET array on Deep Space 1.
- For thermal studies, use combined conduction/radiation thermal analysis models, which calculate the temperature distribution across the radiator which dissipates waste heat from the solar cell to deep space. The accuracy of these conduction/radiation models has been verified by the measured temperatures on the SCARLET array, which matched pre-flight predictions.
- For mass studies, use mass estimation spreadsheets, which include the areas, thicknesses, and densities of the components making up the concentrator array, including lenses, radiators, and photovoltaic cell assemblies.

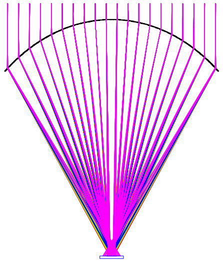


Program Tasks and Schedule

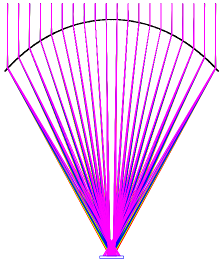
Months After Go-Ahead

Task	Description	1	2	3	4	5	6	7	8	9	10	11	12
1	Generate Conceptual Designs												
2	Perform Parametric Analysis												
3	Concept Down-selection and Refinement												
4	Roadmapping for Future SSP Concentrator Arrays												
5	Reviews and Reports												
6	Educational Outreach Component												

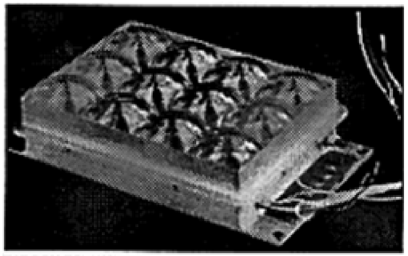
ENTECH, INC.



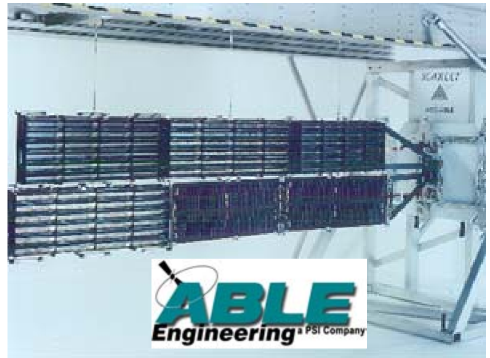
Background and Heritage



Heritage: Space Fresnel Lens Multi-Junction-Cell Photovoltaic Concentrators

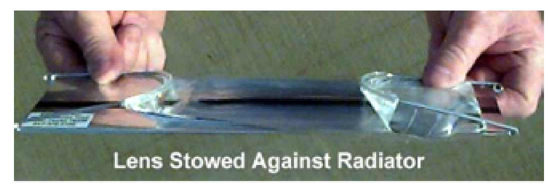


Mini-Dome Lenses on PASP+ in 1994

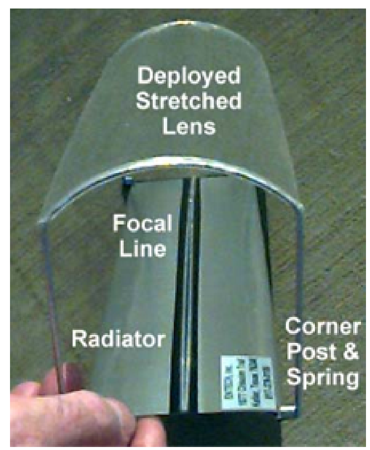


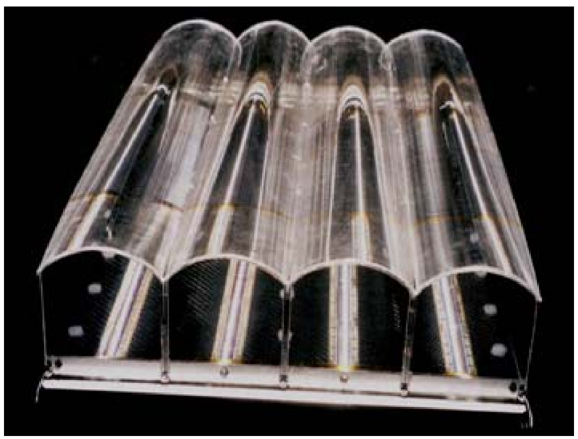
SCARLET 1 Lenses on COMET/METEOR in 1995

SCARLET 2 Lenses on Deep Space 1 in 1998



Stretched Lens in 1998



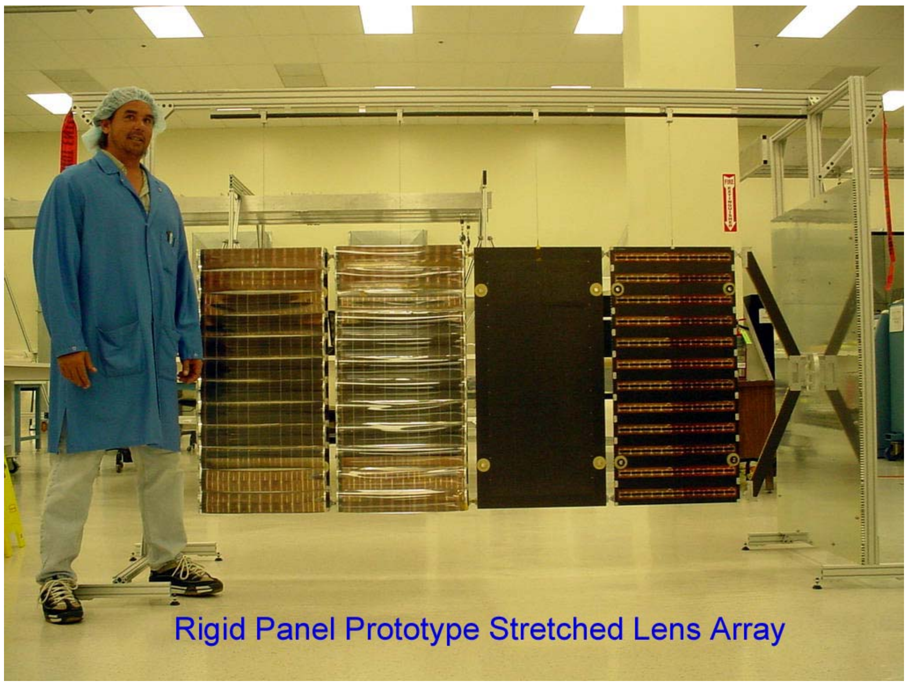


Stretched Lenses and Photovoltaic Receivers in 2000: 27% Net Module Efficiency

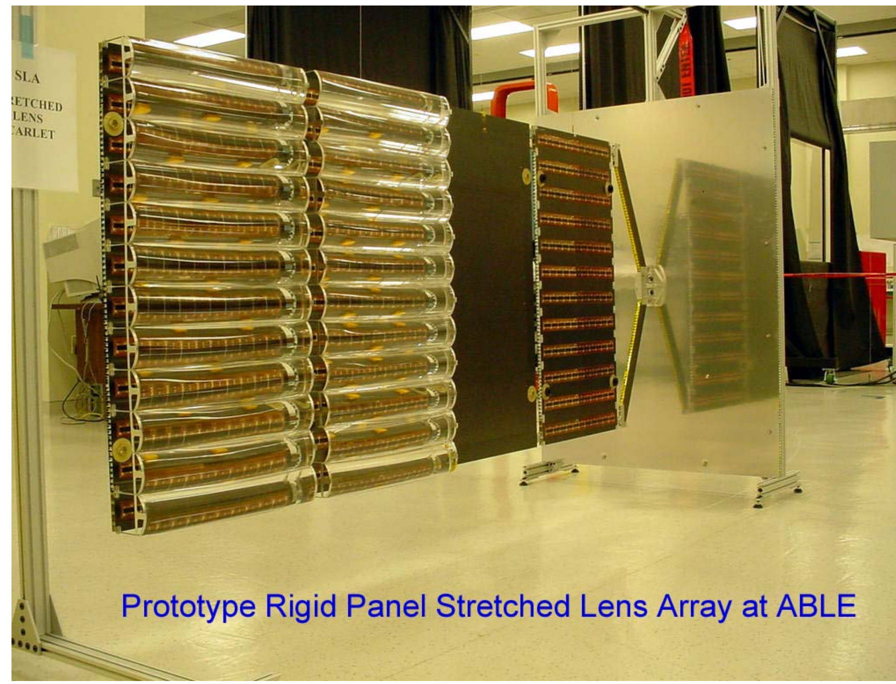
ENTECH, INC.

Rigid Panel SLA Prototype Array at ABLE

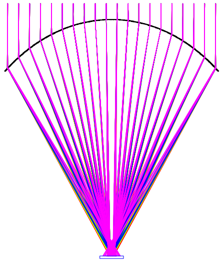
ABLE Engineering a PSI Company



Rigid Panel Prototype Stretched Lens Array

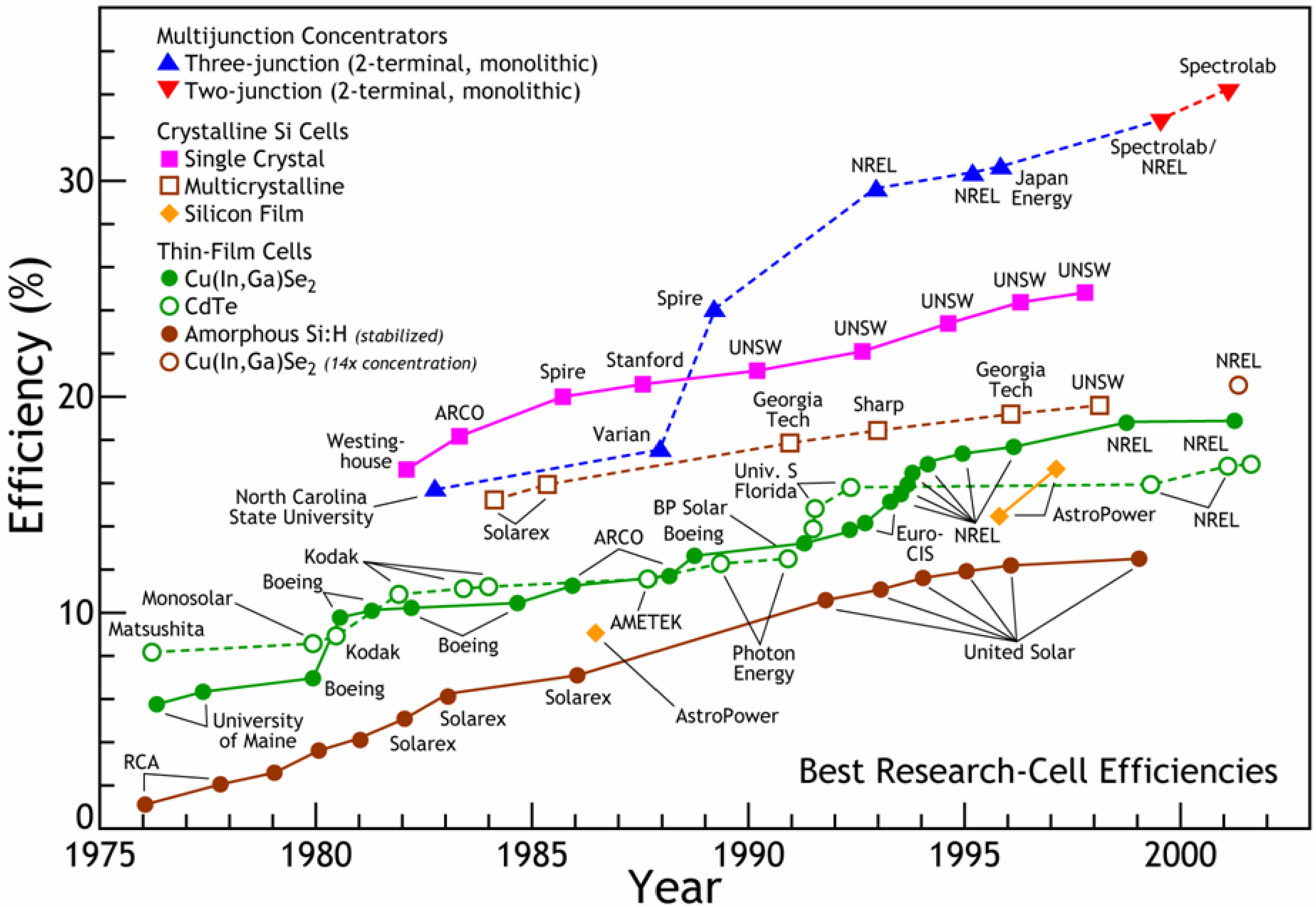


Prototype Rigid Panel Stretched Lens Array at ABLE

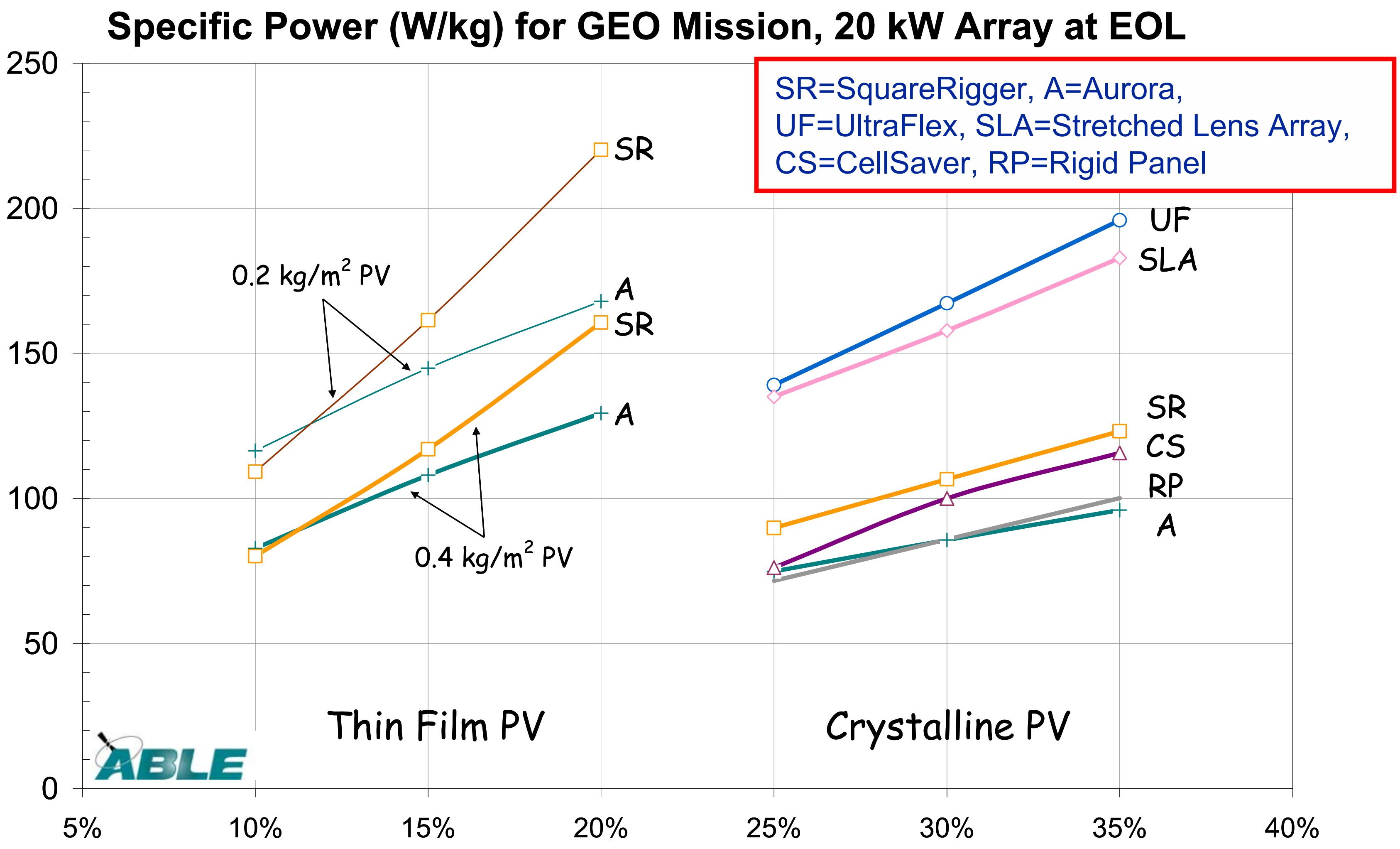


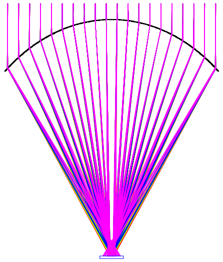
Rationale

Terrestrial Cell Efficiencies Over Time – from DOE's Strategic Program Review March 2002

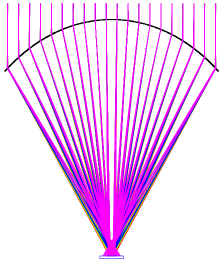


GEO Mission Array Comparisons
(from Murphy et al., IEEE PVSC, 5/02)

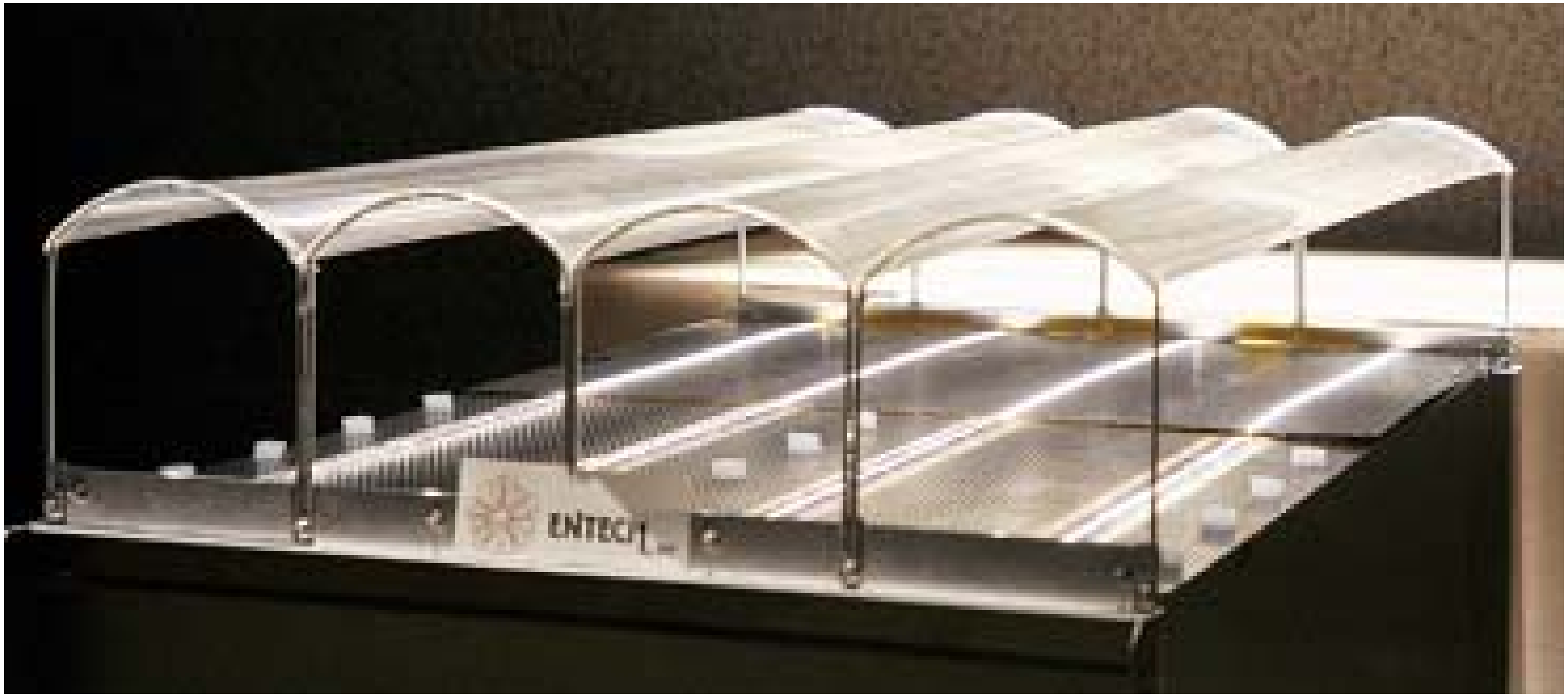


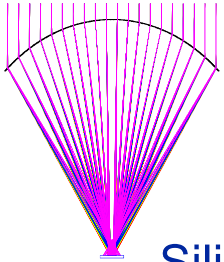


Concepts to Be Studied

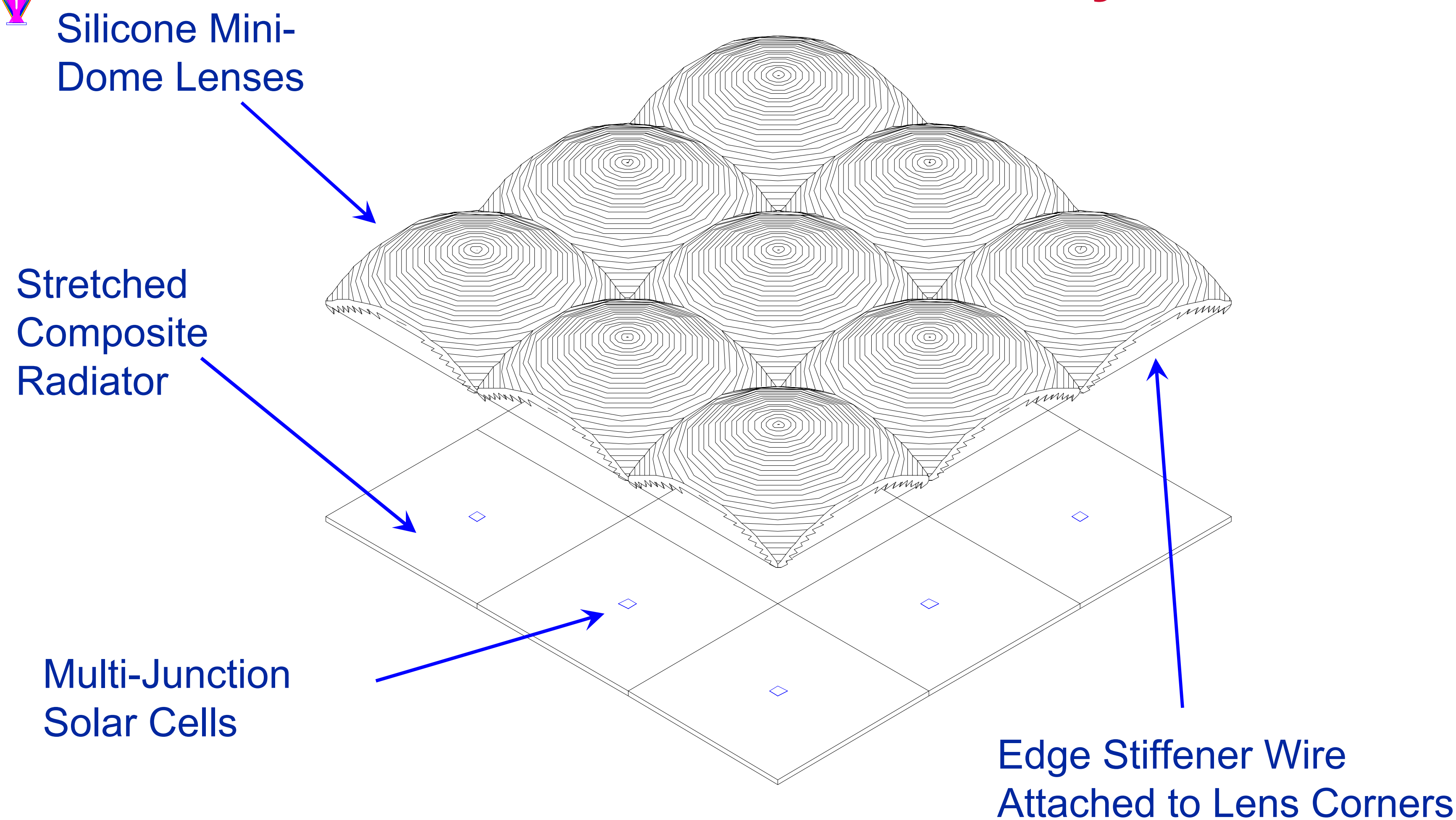


Advanced Stretched Lens Linear Concentrator Blankets



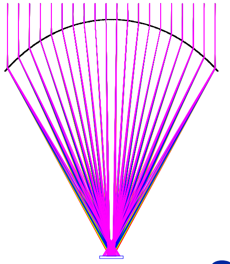


Conceptual Design of Advanced Mini-Dome Lens Array

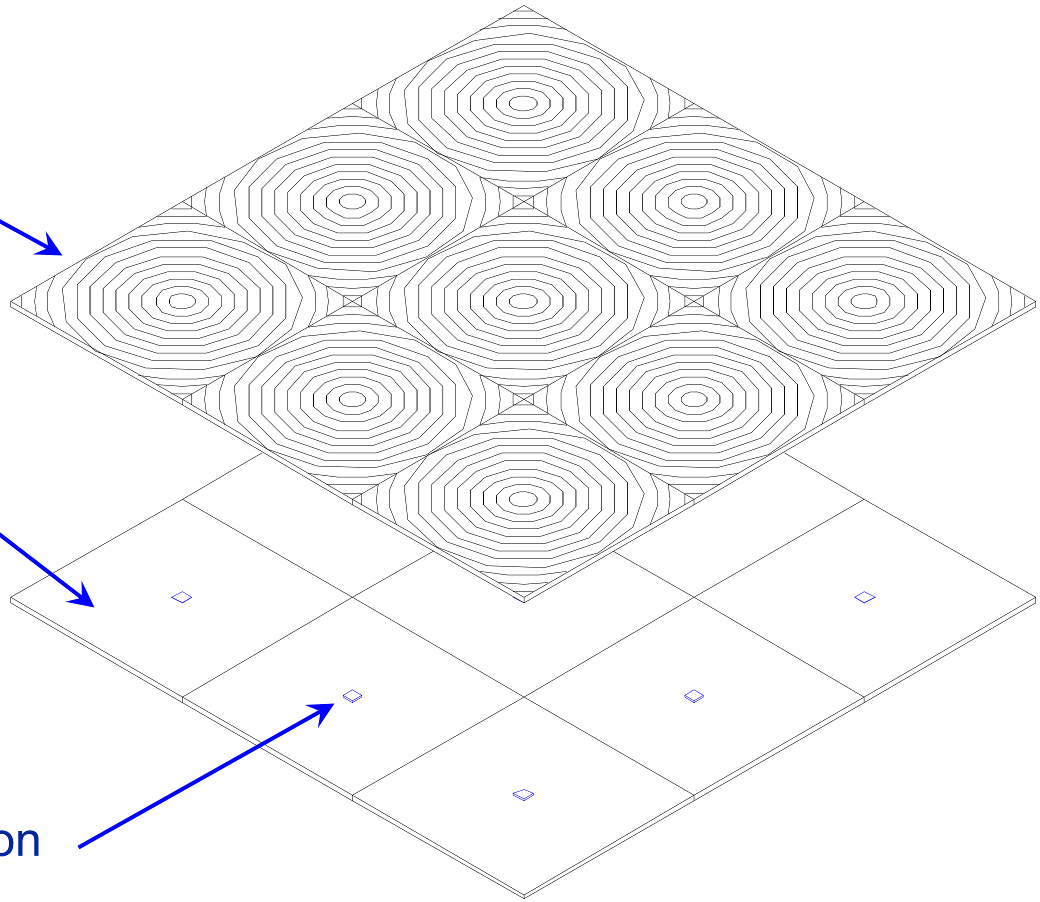


Flexible Domes Could Be Supported in Small Groups with Tensioned Edge Wires Providing Lens Layer Support

ENTECH, INC.



Conceptual Design of Flat Fresnel Lens Array



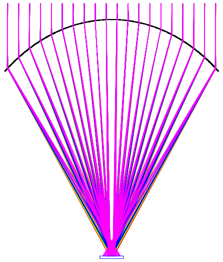
Stretched Membrane Silicone Lenses

Stretched Composite Radiator

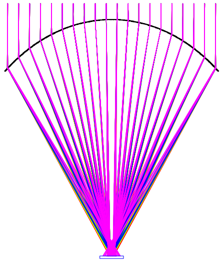
Multi-Junction Solar Cells

Optical Performance Will Suffer Compared to Arched or Dome Lens Designs, But Membrane Support Will Be Easier

ENTECH, INC.

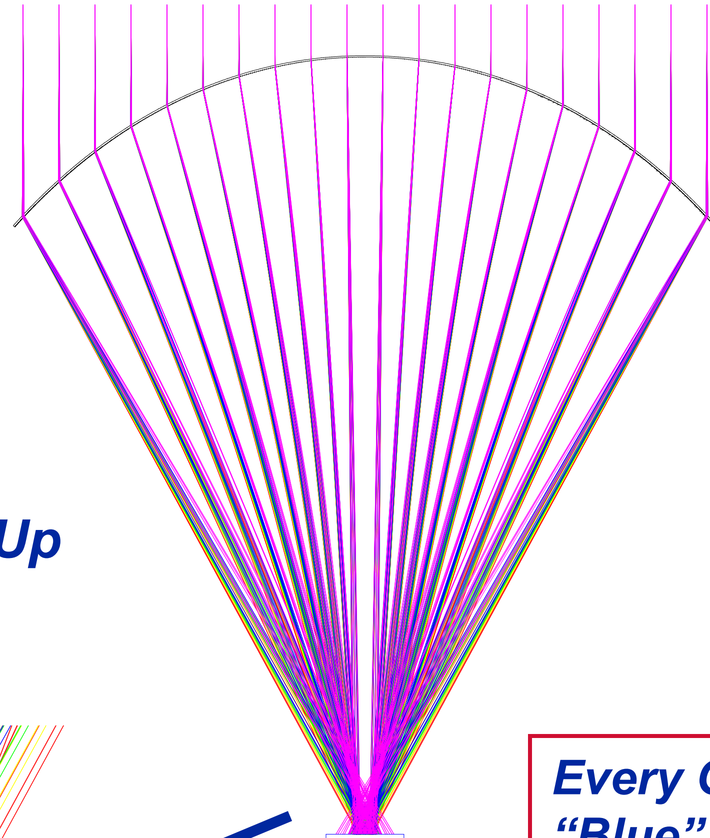


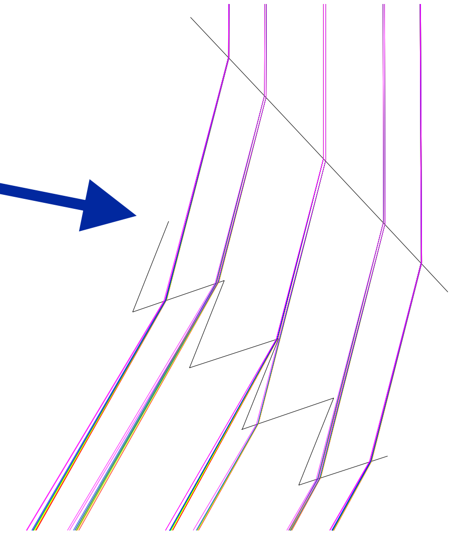
Optical Analysis Approach



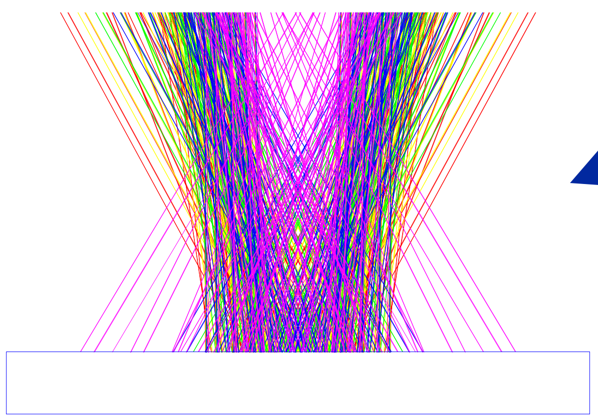
Ray Trace for Color-Mixing Fresnel Lens

U.S. Patents
4,069,812
6,031,179
6,075,200





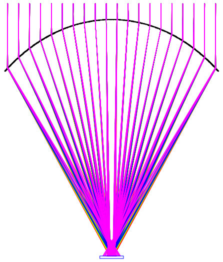
Receiver Close-Up



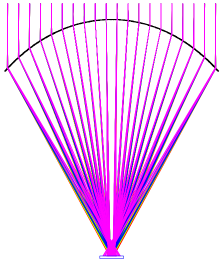
Lens Close-Up

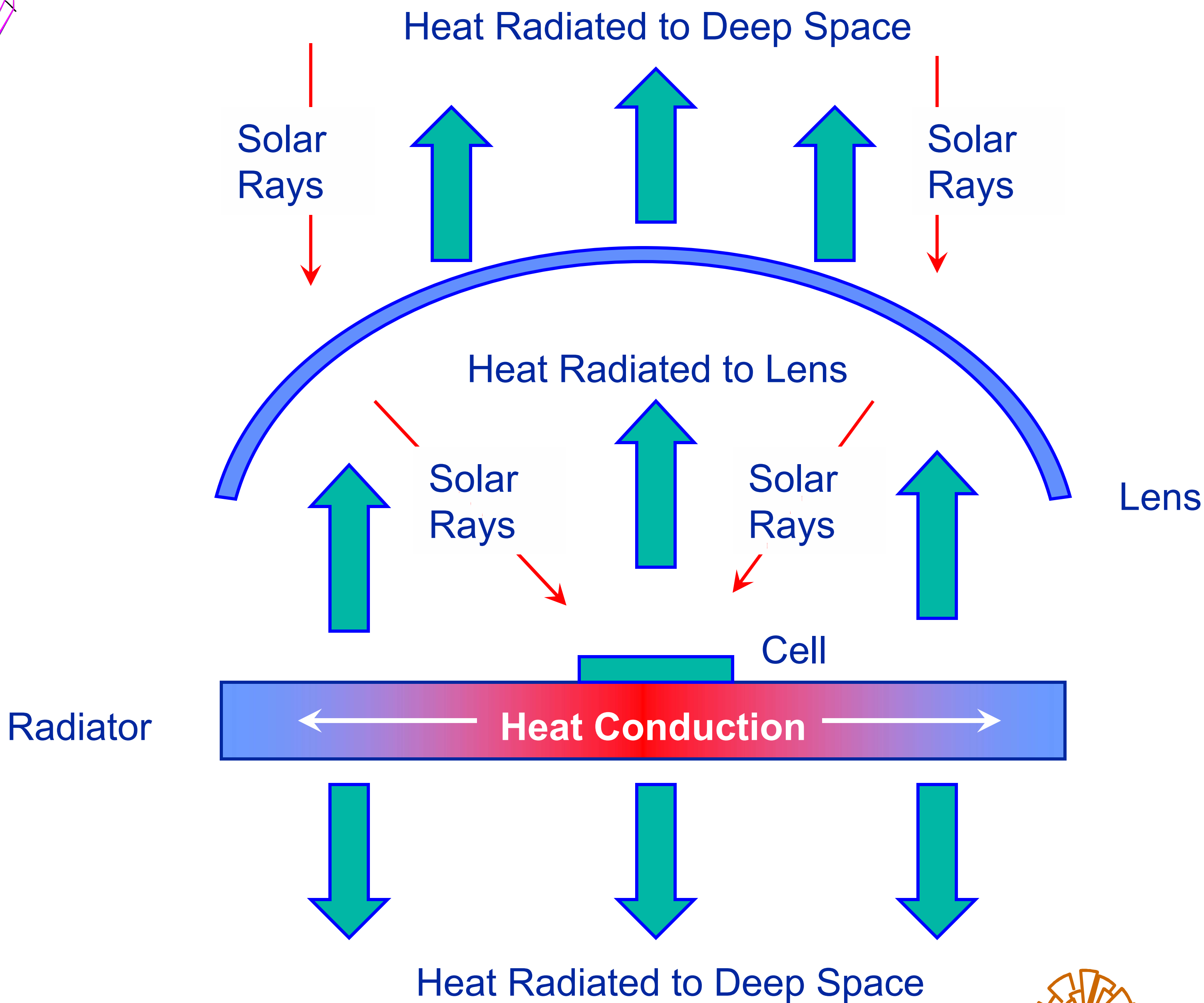
Every Other Prism Overlaps the "Blue" in Its Image with the "Red" in the Neighboring Prism's Image

ENTECH, INC.



Thermal Analysis Approach




Heat Radiated to Deep Space
Solar Rays
Solar Rays
Heat Radiated to Lens
Solar Rays
Solar Rays
Lens
Cell
Radiator
Heat Conduction
Heat Radiated to Deep Space

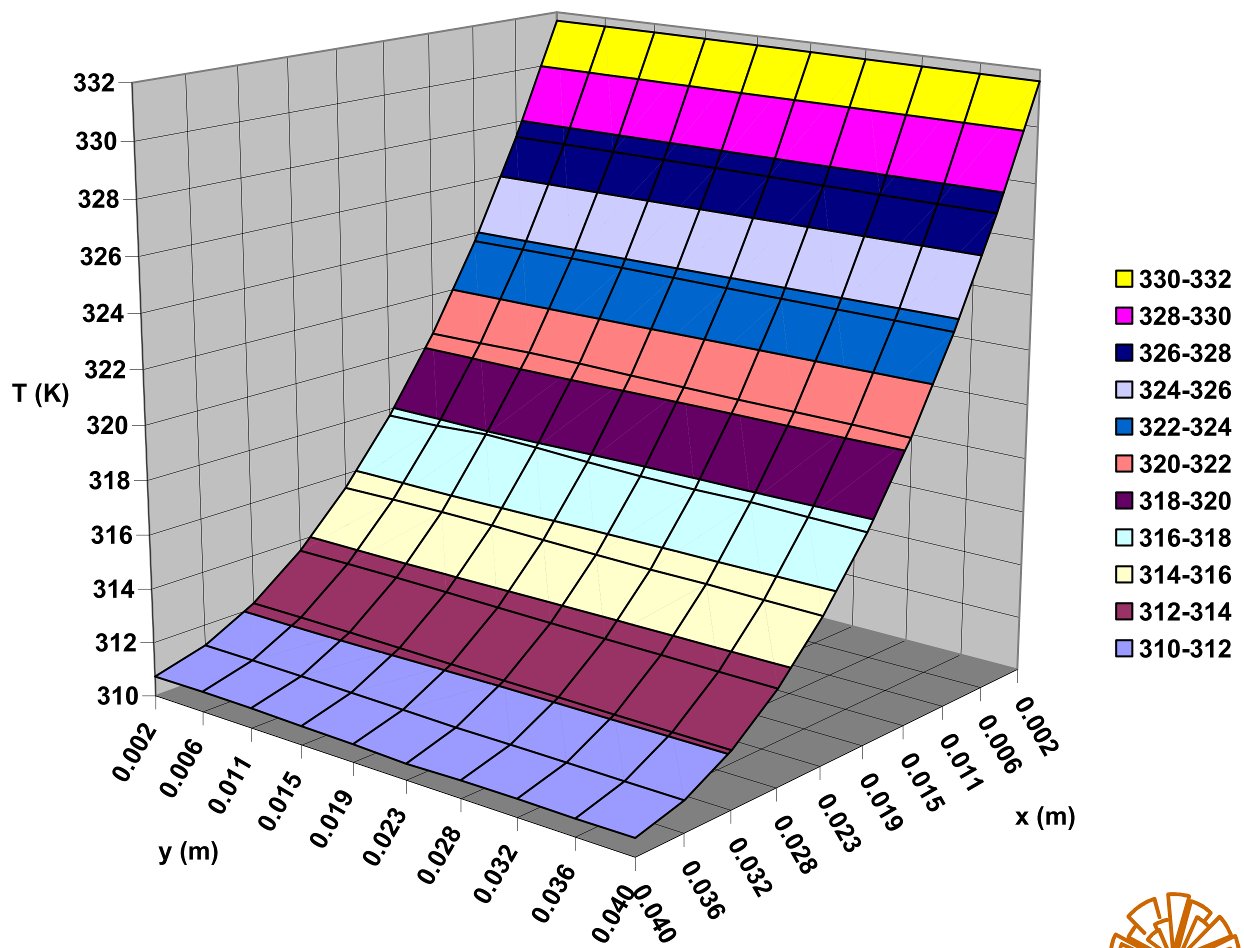
ENTECH, INC.

Thermal Analysis: Line Focus with 30% Cells

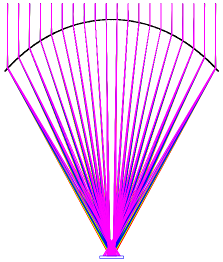
10X Linear Lens Radiator Thermal Analysis

8.5 cm Aperture Width, 30% Cell, 127 micron Radiator Thickness, GEO Orbit

Max Radiator Temperature Just Beneath Cell = 332K (59C)



ENTECH, INC.

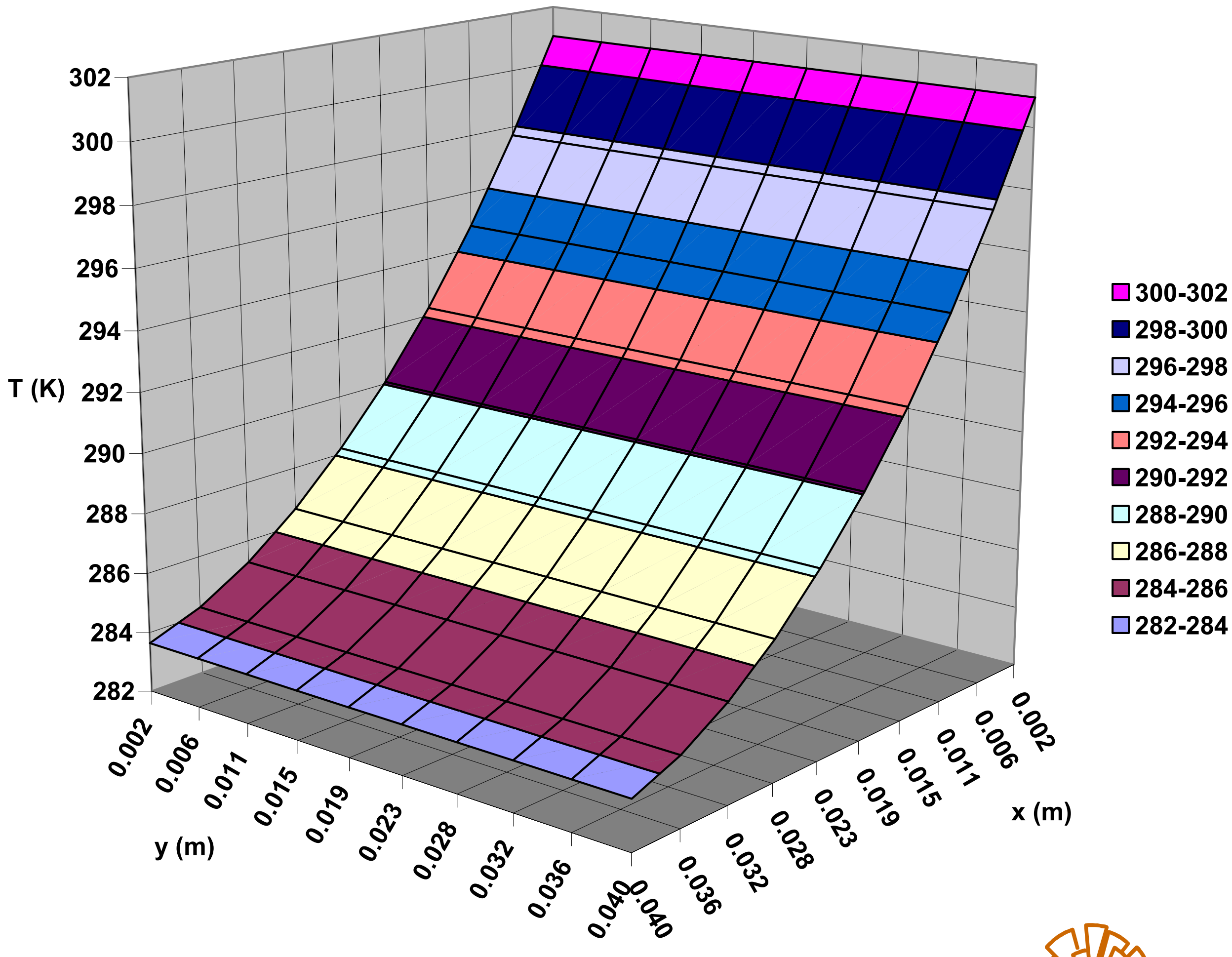


Thermal Analysis: Line Focus with 50% Cells

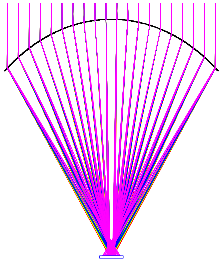
10X Linear Lens Radiator Thermal Analysis

8.5 cm Aperture Width, 50% Cell, 127 micron Radiator Thickness, GEO Orbit

Max Radiator Temperature Just Beneath Cell = 301K (28C)



ENTECH, INC.

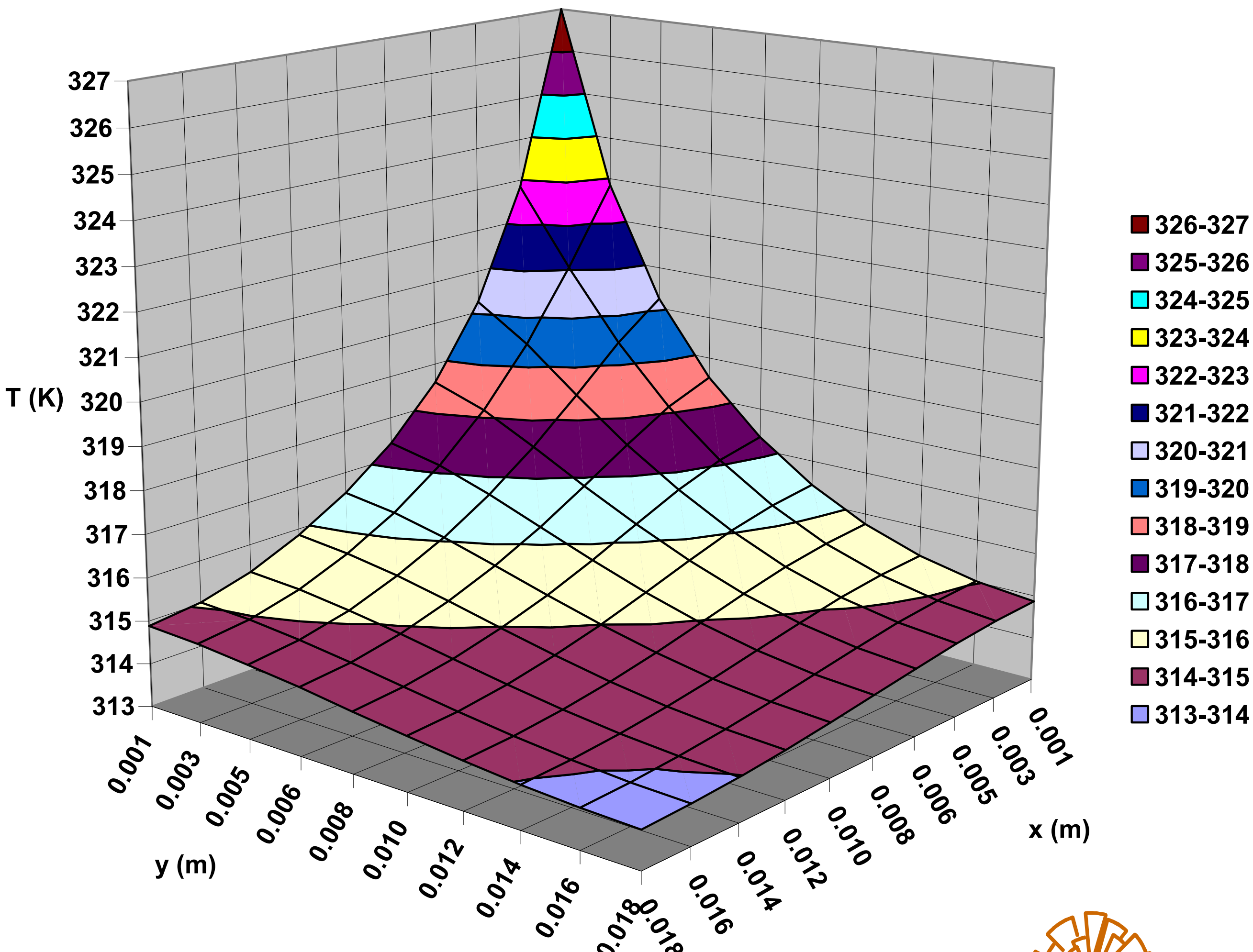


Thermal Analysis: Point Focus with 30% Cells

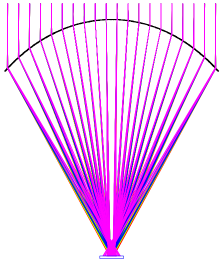
100X Mini-Dome Lens Radiator Thermal Analysis

3.7 cm x 3.7 cm Aperture Area, 30% Cell, 127 micron Radiator Thickness, GEO Orbit

Max Radiator Temperature Just Beneath Cell = 327K (54C)



ENTECH, INC.

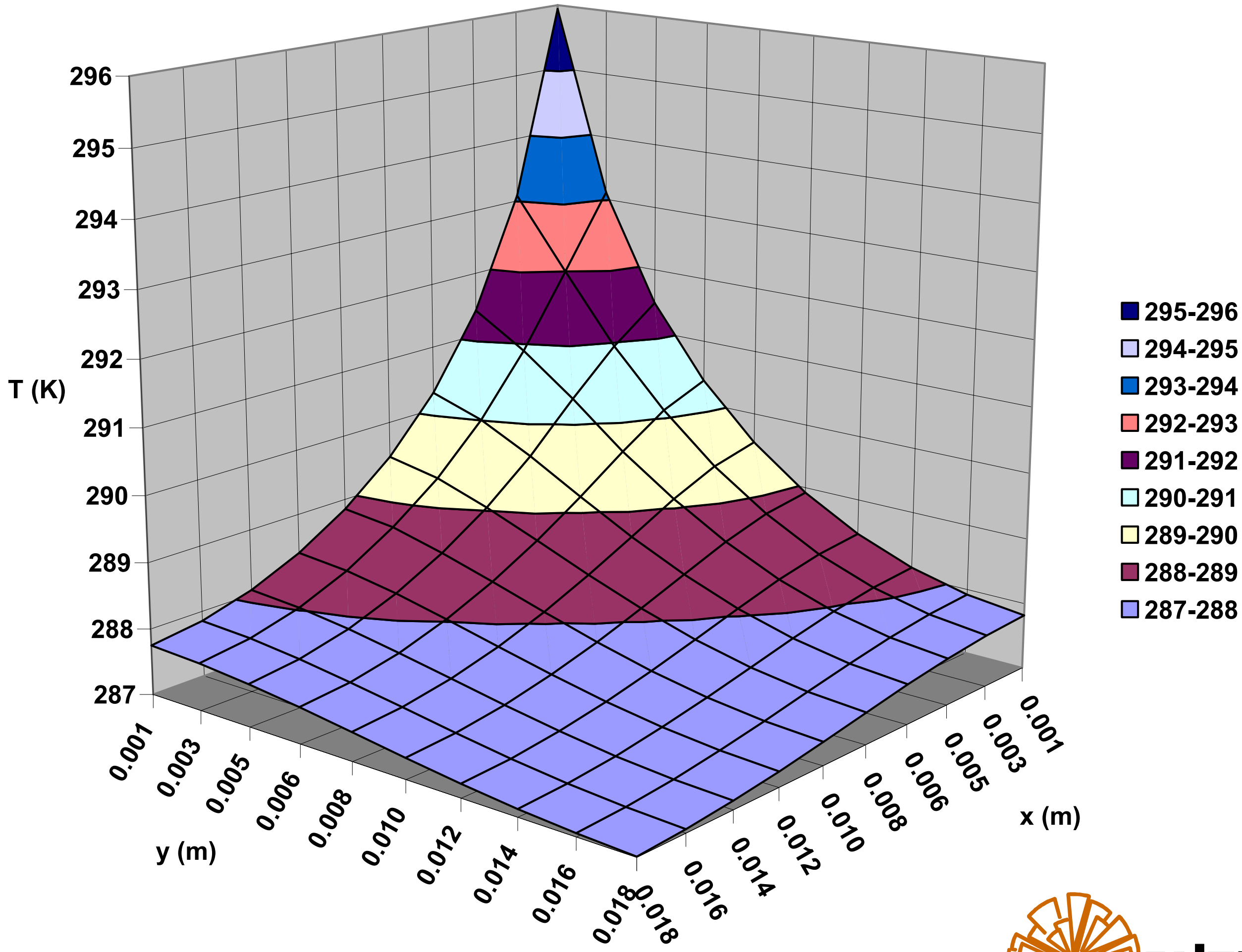


Thermal Analysis: Point Focus with 50% Cells

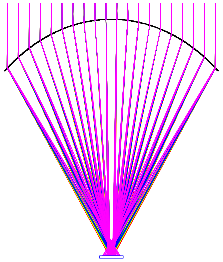
100X Mini-Dome Lens Radiator Thermal Analysis

3.7 cm x 3.7 cm Aperture Area, 50% Cell, 127 micron Radiator Thickness, GEO Orbit

Max Radiator Temperature Just Beneath Cell = 296K (23C)

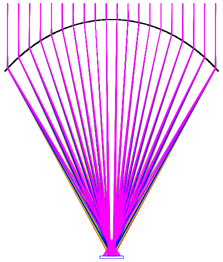


ENTECH, INC.



Areal Mass Density Analysis Approach

ENTECH, INC.



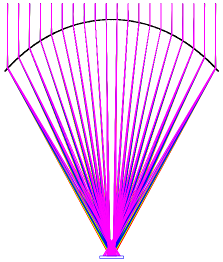
Example Areal Mass Density Calculation for Functional Concentrator Elements

Areal Mass Density of Active Lens, Radiator Sheet, and Photovoltaic Receiver Elements						
Geometric Concentration Ratio		100 X				
Major Subsystem	Element	Element Area per sq.m. Aperture	Thickness	Density	Mass/Aperture	Subtotals: Mass/Aperture
		(sq.m.)	(cm)	(g/cu.cm.)	(kg/sq.m.)	(kg/sq.m.)
Lens	Silicone Lensfilm	1.200	0.014	1.080	0.181	0.181
Radiator	Graphite/Cyanate Radiator	1.000	0.013	1.750	0.219	0.219
Receiver	Cell Prism Cover	0.010	0.025	1.080	0.003	0.016
	Germanium Cell Wafer	0.010	0.014	5.300	0.007	
	Conductive Silicone Adhesive	0.010	0.005	3.400	0.002	
	Flex Circuit Copper Traces	0.010	0.004	8.930	0.004	
	Flex Circuit Polyimide Film	0.010	0.005	1.500	0.001	
	Silicone Adhesive	0.010	0.003	1.080	0.000	
Total					0.417	0.417 kg/sq.m.

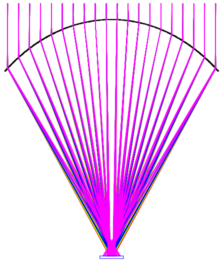
At SSP System Implementation	
Cell Efficiency	50%
Lens Efficiency	92%
Combined Efficiency	46%
Areal Power Density	629 W/sq.m.
Specific Power	1,509 W/kg

Summary of Parametric Results		
8.5 X	0.582 kg/sq.m.	1,081 W/kg
25 X	0.466 kg/sq.m.	1,349 W/kg
100 X	0.417 kg/sq.m.	1,509 W/kg

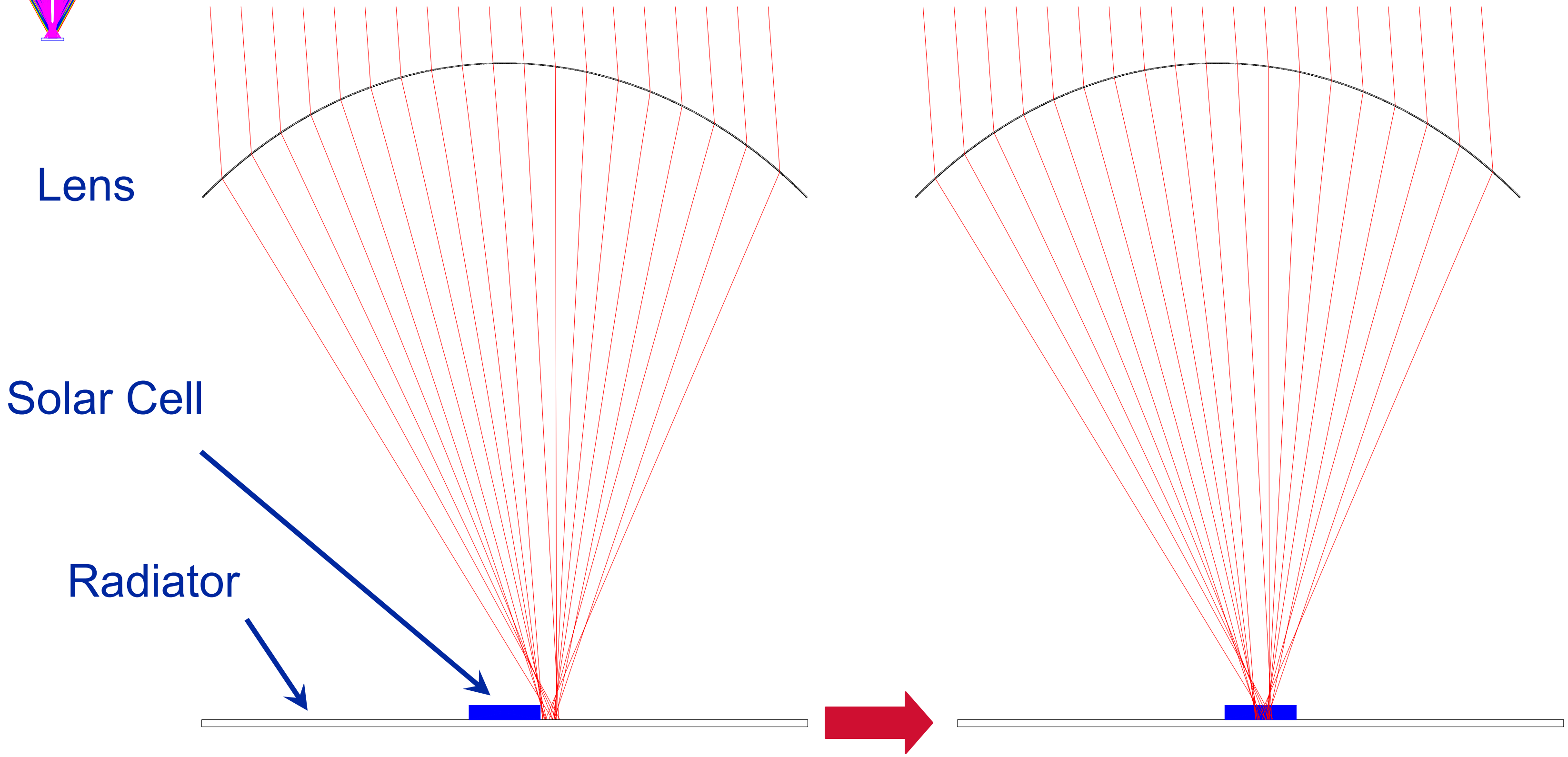
ENTECH, INC.



Basic Concept for Local Adaptive Techniques to Accommodate Local Deflections and Distortions Over Gigantic Concentrator Arrays



Adaptive Techniques Could Be Used to Accommodate Large SSP Deflections

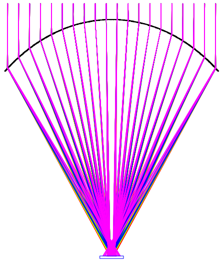


Local Deflections on Square-Kilometer Scale SSP Arrays Could Cause Local Image-to-Cell Misalignment

But Adaptive Techniques Could Be Used to Translate the Local Cell/Radiator Relative to Lens to Accommodate These Deflections

A Flimsy Blanket Array with Large Deflections Can Work with a Concentrator Approach with Proper Adaptive Accommodation

ENTECH, INC.

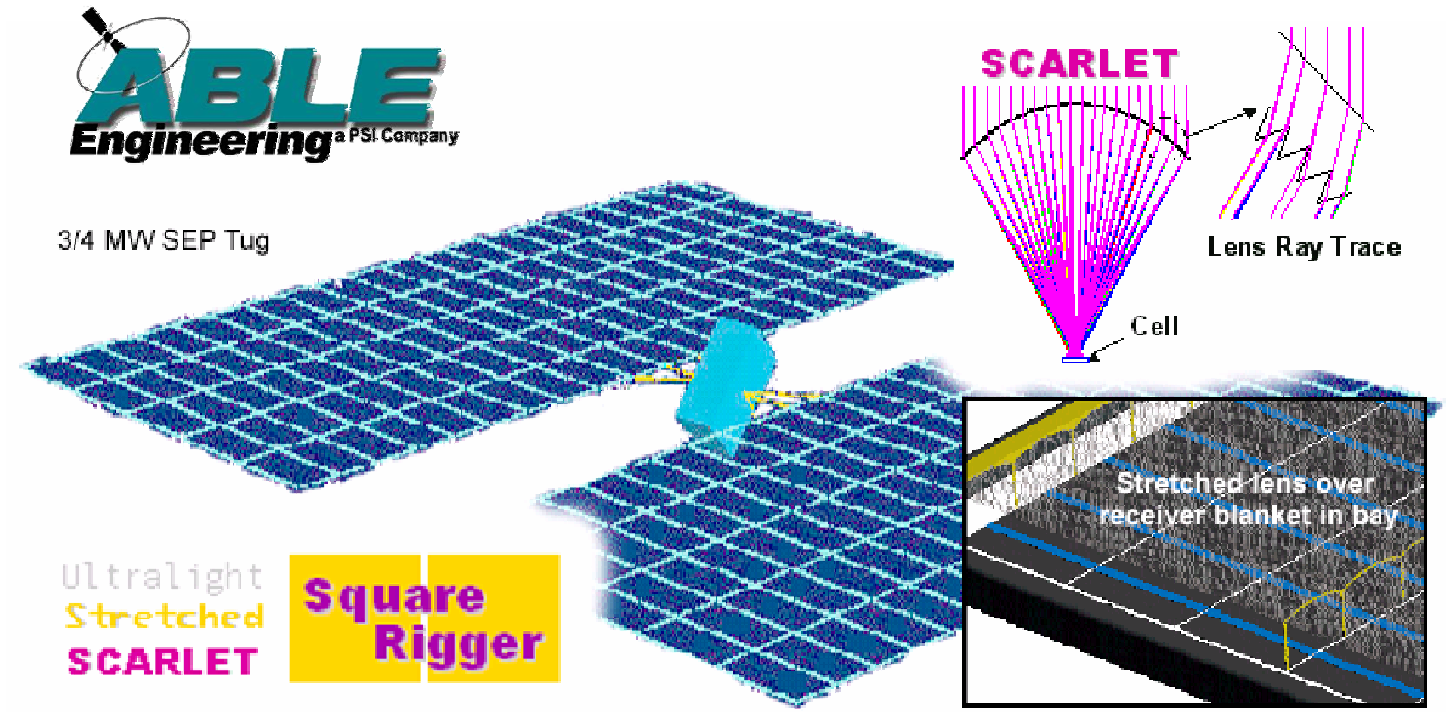


The Ideal Ultra-Light, Scalable Platform for Deployment and Support of Advanced Concentrator Arrays:

ABLE's SquareRigger

ENTECH, INC.

A Marriage Made in Heaven: ABLE's SquareRigger Platform and ENTECH's Stretched Lens Array



USS SquareRigger

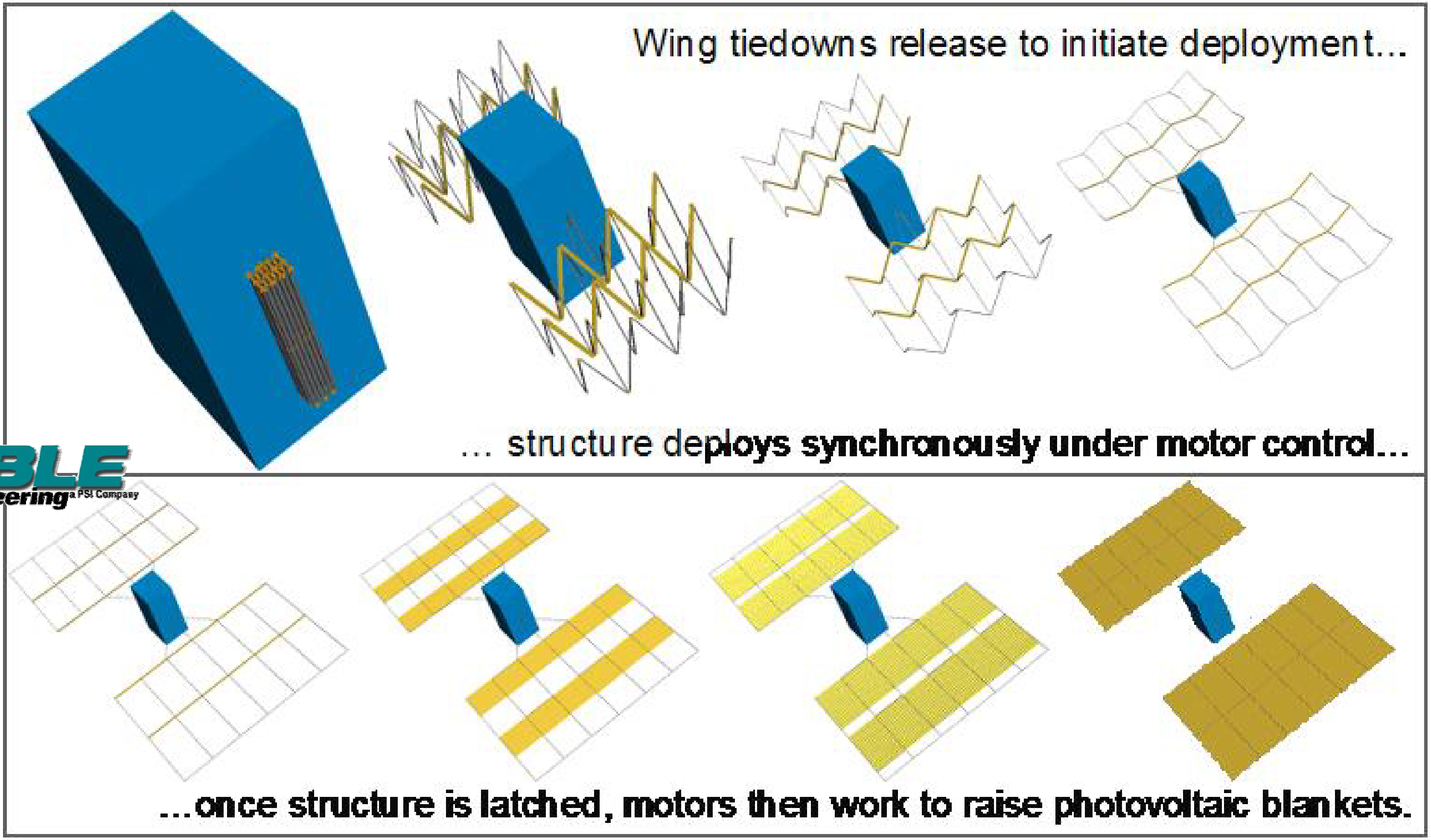
Time Frame	< 5 Years	5-10 Years
Power Capability (kW)	100	1,000
BOL Specific Power (W/kg)	330	500
Stowed Power (kW/m^3)	80	120
Voltage	1,000	TBD

Applicable to: All NASA, DOD, and commercial spacecraft requiring high power, including:

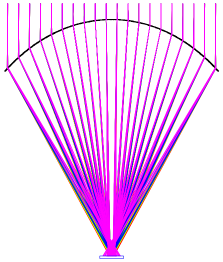
- GEO communication satellites
- Interplanetary SEP spacecraft
- Space Solar Power
- SEP Orbital Tugs

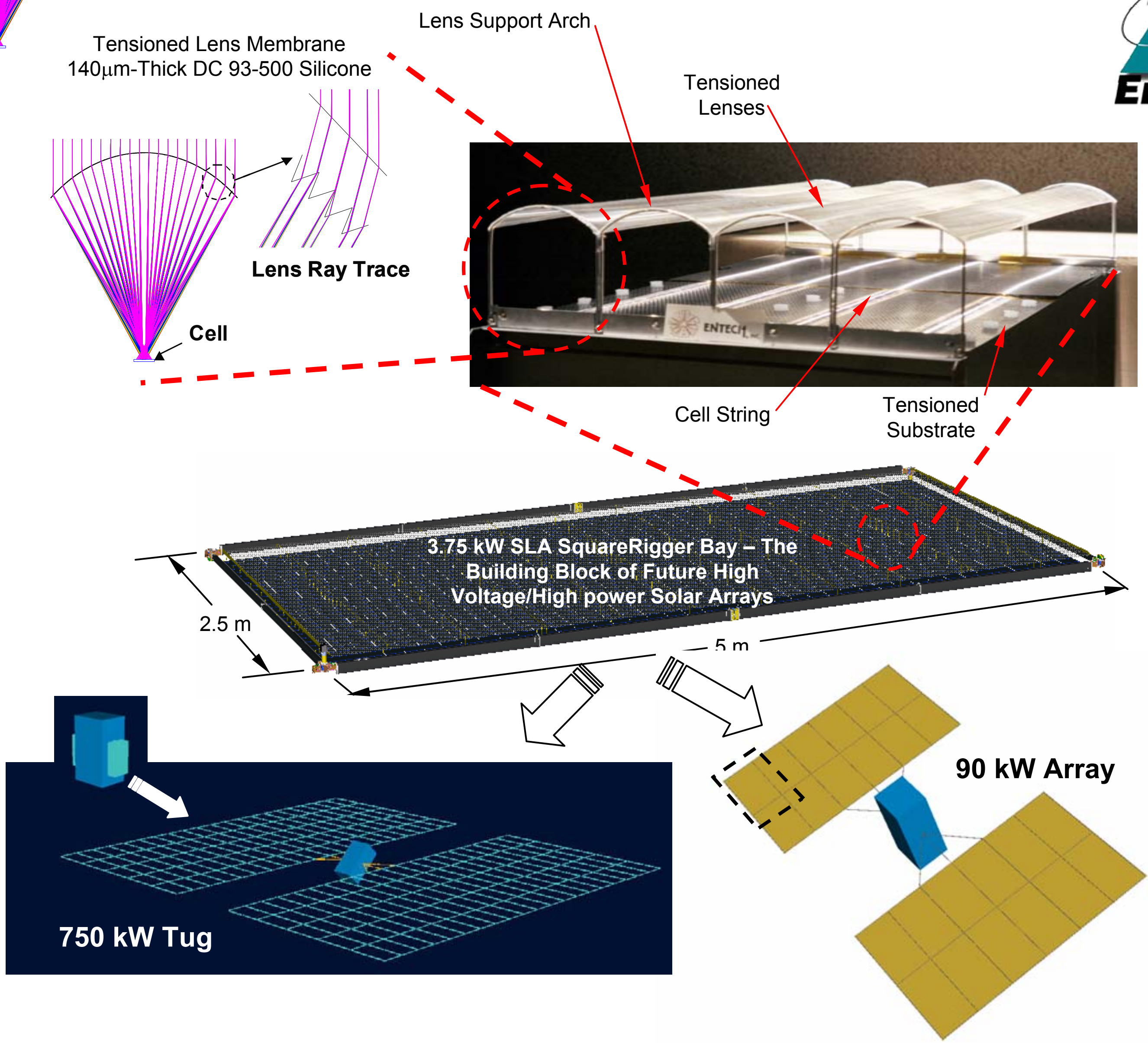
ENTECH, INC.

ABLE's SquareRigger Platform: Originally Developed for AFRL for Thin-Film Photovoltaics



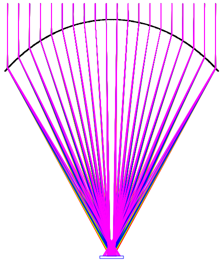
Ultralight Stretched SCARLET (USS) SquareRigger Concept



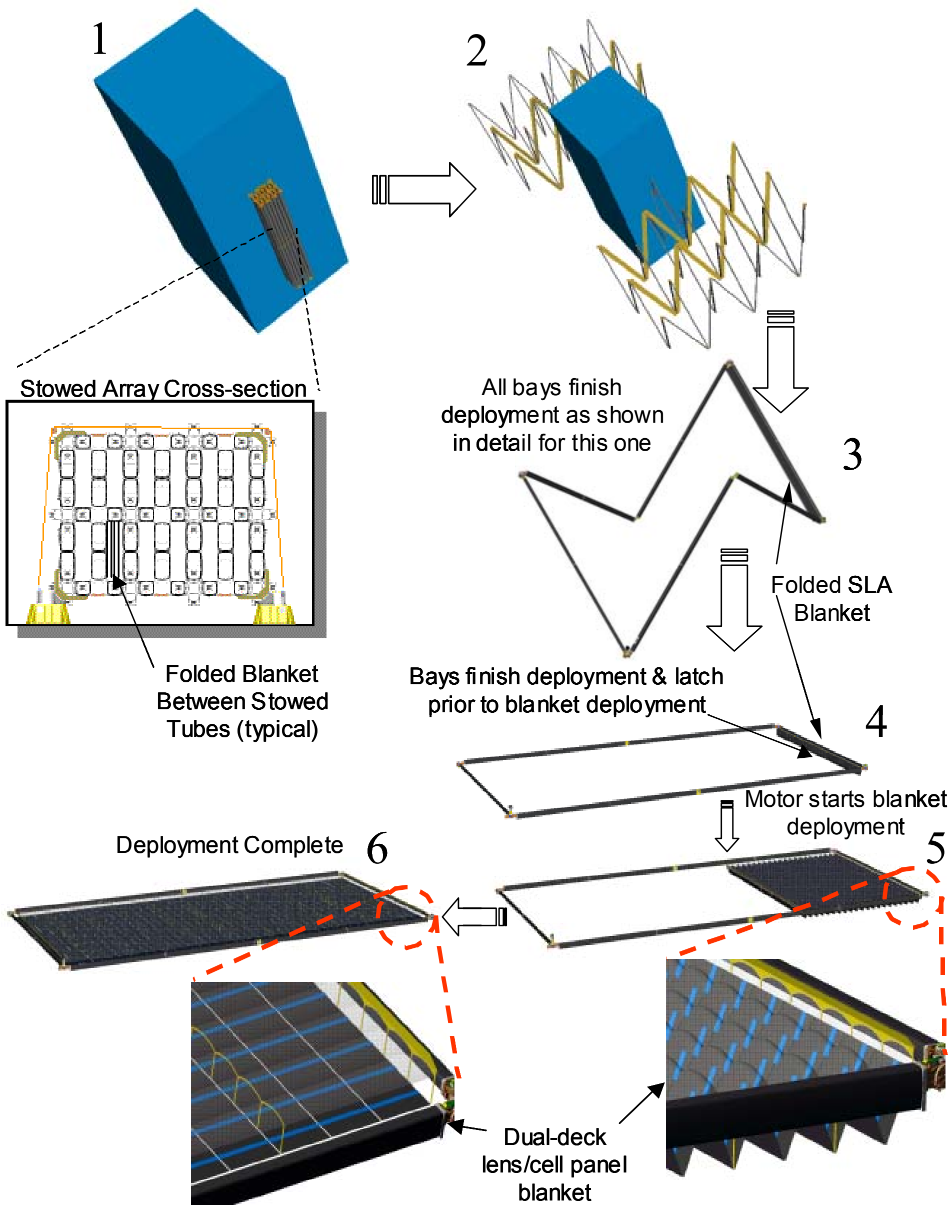


ABLE Engineering a PSI Company

ENTECH, INC.

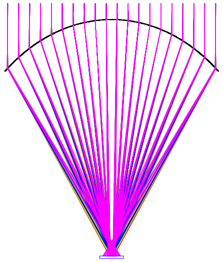


USS SquareRigger Deployment



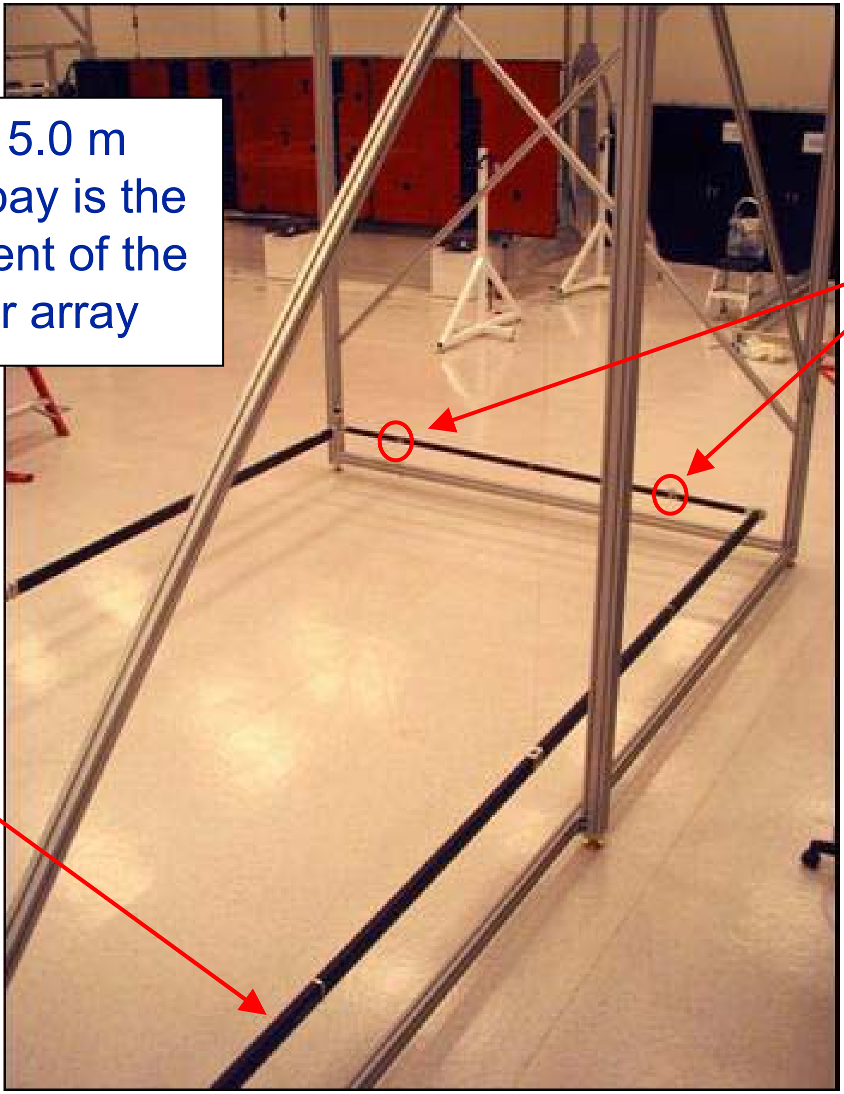
ABLE Engineering a PSI Company

ENTECH, INC.



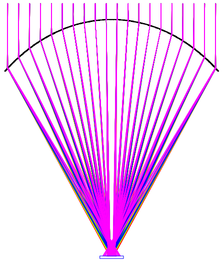
Full-Scale SquareRigger Bay Deployment

This 2.5 m x 5.0 m SquareRigger bay is the repeating element of the SquareRigger array

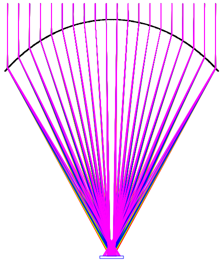


Ports for blanket deployment/ tensioning cables

Low mass composite tube



Conclusions



Conclusions

- **Refractive Concentrators Using Multi-Junction Cells Represent the Most Efficient Option for Converting Sunlight to Electricity for Either Space or Ground Solar Power Applications**
- **Today's Demonstrated Lens/Cell Module Efficiencies Are 27% in Space and 30% on the Ground – Future Efficiencies at SSP Implementation (e.g., 2022) Should Nearly Double Based on Cell Efficiency Trends**
- **Compared to Thin Film Arrays, Refractive Concentrator Arrays Will Be 2-4X More Efficient, 2-4X Smaller in Size, and Equal or Better in Terms of W/kg and $/W at the System Level**
- **Work Should Continue on Advanced Concentrator Arrays for SSP, Including Advanced Ultra-Light Concepts and Simple Means to Accommodate Large Deflections on Square-Kilometer Size Arrays, Using Techniques from Adaptive Optics, Smart Materials, Shape Memory Alloys, etc.**

ENTECH, INC.